Effect of copper on austempering behavior of ductile iron

Thesis submitted in partial fulfillment of the requirements for the degree of

Master of Technology

In

Metallurgical & Materials Engineering

By

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National Institute of Technology, Rourkela.

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2011

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ROURKELA

CERTIFICATE

This is to certify that, the work embodied in this project report entitled **"Effect of copper on austempering behavior of Ductile iron"** by Shri Ranjit Kumar Panda is an authentic record of work carried out by him under our supervision and guidance for partial fulfillment of the requirements for the degree of Master of Technology in Metallurgical and Materials engineering; National Institute of Technology, Rourkela.

To the best of our knowledge, this work has not been submitted to any other University/institute for the award of any degree or diploma.

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Date: 20.05.2011 **Ranjit Kumar Panda**

Contents

Abstract

Even since its discovery in 1948, the use of ductile iron is increasing continuously, this is due to the combination of its various excellent mechanical properties. Excessive amount of research is being carried out to develop even better properties. Austempererd ductile iron is the most recent development in the area of ductile iron or S.G. iron. This is formed by an isothermal heat treatment of the ductile iron. The newly developed austempered ductile iron is now replacing steel in many fields so it has becoming very important to various aspects of this material. In the present work the effect of copper along with the process variables (austempering temperature and austempering time) on the properties (Hardness, Tensile strength and Elongation) and microstructure of ductile iron is studied. With increasing austempering time hardness, tensile strength and elongation are increasing but with increasing austempering temperature hardness and tensile strength are decreasing and elongation increasing. Austempered ductile iron with copper is showing some higher strength, hardness and lower elongation than the austempered ductile iron without copper. In microstructure ferrite is increasing with increasing austempering time and austenite is increasing with increasing austempering temperature in both the grades.

Key words: S.G. Iron, Austempering, austempered ductile iron, austempering time and temperature, austenite and ferrite

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Introduction

CHAPTER 1 Introduction

In recent years, there has been a significant importance in energy saving which has led to the advancement of light weight, durable and cost effective materials. For these purpose, there is a requirement to continually formulate new materials and checkout those already in account. One such material is ductile iron. Research efforts on this material, have mainly, focused on possible improvements of mechanical properties by subjected it to appropriate heat treatment and by alloying elements.

A ductile iron which subjected to a peculiar isothermal heat treatment process austmpering is known as austempered ductile iron (ADI). The properties of Austempered ductile iron is produced by the particular heat treatment so the only essential for austempered ductile iron is better ductile iron.

Ductile Cast Iron undergoes a remarkable transformation when subjected to the austempering heat process. The resulting microstructure, known as "Ausferrite",which consist of fine acicular ferrite with carbon enriched stabilized austenite(2) and gives ADI its special attributes. The new microstructure (ADI) results with capability superior to many traditional, high performance, ferrous and aluminium alloys. Ausferrite exhibits twice the strength for a given level of ductility compared to the pearlitic, ferritic or martensitic structures formed by conventional heat treatments.

The mechanical properties of the austempered ductile iron are depending on the ausferrite microstructure. The austepmered matrix is responcible for significantly better tensile strength to ductility ratio than is possible with any other grade of ductile iron (1).

An unusual combination of properties is obtained in austempered ductile iron because of the ausferrite microstructure. These properties mainly depend on the heat treatment conditions and alloyed elements. Alloy additions may be made to austempered ductile iron with a view to control the matrix structure.

In present research work, the effect of copper alloying as well as the effect of heat treatment parameters like austmpering time and austempering temperature on microsteucture and properties of the ductile iron were studied.

Chapter 2
Literature review

CHAPTER 2 Literature review

Cast irons are basically alloys of iron and carbon like steels but contain greater amount of carbon. Cast irons contain between 2 and 6.67% of carbon. High carbon content tends to make the cast iron very brittle and most commercially manufactured types are in the of 2.5 to 4% carbon. The ductility of cast iron is very low. They melt readily and can be cast into complicated shapes. Since casting is the only suitable process applied these alloys, they are known as cast irons. By proper alloying, good foundry control and appropriate heat treatment, the properties of any type of cast iron may be varied over a wide range. The physical properties of the cast iron will greatly influenced by the shape distribution of the free carbon particles. The common cast irons are brittle, have lower strength properties and can be cast more rapidly than most steels. White cast iron, malleable cast iron, gray cast iron, nodular cast iron and alloyed cast iron are different type of cast irons [3].

2.1. Ductile iron

If coke had not been used for melting iron and if high purity ores had been used then ductile iron would have been accepted as normal form of iron [4].Ductile iron is also known as nodular iron, spheroidal graphite iron and spherulitic iron in which graphite is present in tiny balls or spheroids [3]. Because of the graphite is in the form of roughly spherical, which gives these materials their name and ductility significantly improved so alternative name is ductile cast iron. The castability, corrosion resistance, machinability and abrasive resistance are similar to the flake graphite grades but tensile elongation as high as 17% [4].

2.1.1. Back ground

Ductile cast irons represent a triumph of 20^{th} century metallurgical research. These irons were developed independently in approximately 1948 at the International Nickel Company (INCO) in the United States and at the British Cast Iron Research Association (BCIRA) in England. Both groups discovered that by keeping the sulfur and phosphorus levels low and adding very small amounts of a key chemical element, the shape of the graphite could be changed from the interconnected flakes of gray irons into isolated spheres (usually called spheroids) of graphite.

The INCO team showed that the effect was produced by the addition of only 0.02 to 0.1% Mg, and the BCIRA team by the addition of only 0.02 to 0.04% Ce (the rare earth metal of atomic number 58) [5].

2.1.2. Production of SG Iron

SG Irons are produced directly by the solidification of a melt containing sufficient silicon to ensure graphite formation, after careful removal of sulphur and oxygen. Magnesium additions to the bath tie up sulphur and oxygen and radically change the graphite growth morphology. Magnesium reacts with the oxygen to form highly stable MgO, which floats to the surface and can be skimmed off. The oxygen content is reduced from typical levels of 90-135ppm to about15-35ppm. Magnesium also reacts with the sulphur to produce MgS which again floats to the bath surface, but less stable than the oxide. Since magnesium has low solubility in the metal and is volatile, the reactions can become reversible if losses are too great. Silicon in the form of ferro silicon is generally added to provide additional deoxidation. Other elements from groups 1A, 11A and 111A can be also being employed to tie up oxygen and sulpher. In particular cerium forms highly stable oxides and sulphides and less volatile than magnesium, with which it is used in combination. Some of the inclusions formed by the inoculants act as nuclei for the graphite and are found at the center of the nodules. The simplest explanation of the spherodising effect of inoculants such as magnesium is that oxygen and sulphur are absorbed preferentially on the hexagonal planes of graphite, leading to the lamellar morphology. The removal of sulpher and oxygen by the inoculants allows more isotropic growth. A careful choice of alloying additions is used to appropriately adjust the deoxidation, graphitizing and nucleation effects [4].

2.1.3. Chemical composition

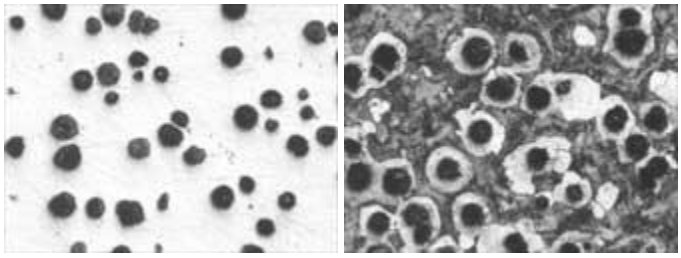
For common cast iron, the main elements of the chemical composition are carbon and silicon. High carbon content increases the amount of graphite or Fe3C. High carbon and silicon contents increase the graphitization potential of the iron as well as its castability. The manganese content varies as a function of the desired matrix. Typically, it can be as low as 0.1% for ferrule irons and as high as 1.2% for pearlitic irons, because manganese is a strong pearlite promoter. From the minor elements, phosphorus and sulfur are the most common and are always present in the

composition. They can be as high as 0.15% for low-quality iron and are considerably less for high-quality iron, such as ductile iron or compacted graphite iron [6].

The main effect of chemical composition in nodular (ductile) iron is on graphite morphology. The carbon equivalent has only a mild influence on the properties and structure of ductile iron, because it affects graphite shape considerably less than in the case of gray iron. Nevertheless, to prevent excessive shrinkage, high chilling tendency, graphite flotation or a high impact transition temperature, optimum amounts of carbon and silicon must be selected. Minor elements can significantly alter the structure in terms of graphite morphology, chilling tendency, and matrix structure. Minor elements can promote the spheroidization of graphite or can have an adverse effect on graphite shape [6].

2.1.4. Structure

The main difference between ductile iron and grey iron is the morphology of graphite particles which take on a nodular or almost spherical form after suitable treatments are made to the melt. The major micro structural constituents of ductile iron are: the chemical and morphological forms taken by carbon, and the continuous metal matrix in which the carbon and/or carbide are dispersed. The following important microstructural components are found in ductile iron [7].



(a) (b)

Fig 2.1.Mirostructure of ductile iron (a) unethed (b) nital etched :100X [19].

2.1.4.1. Graphite

This is the stable form of pure carbon in cast iron. Its important physical properties are low density, low hardness and high thermal conductivity and lubricity. Graphite shape, which can range from flake to spherical, plays a significant role in determining the mechanical properties of ductile irons. Ductile iron is characterized by having all of its graphite occurs in microscopic

spheroids. Although this graphite constitutes about 10% by volume of ductile iron, its compact spherical shape minimizes the effect on mechanical properties [8].

2.1.4.2. Ferrite

This is the purest iron phase in a cast iron. In conventional Ductile Iron ferrite produces lower strength and hardness, but high ductility and toughness. In Austempered Ductile Iron (ADI), extremely fine grained acicular ferrite provides an exceptional combination of high strength with good ductility and toughness. The strength properties of ferritic ductile iron are generally increased by the elements, which go in to the solution. With the exception of carbon, all the elements increase tensile strength and hardness. An example of the extent to which ferrite is affected by solid solution strengthening is illustrated for the elements silicon and nickel [8].

2.1.4.3. Pearlite

Pearlite, produced by a eutectoid reaction, is an intimate mixture of lamellar cementite in a matrix of ferrite. A common constituent of cast irons; pearlite provides a combination of higher strength and with a corresponding reduction in ductility which meets the requirements of many engineering applications [8].

2.1.4.4. Martensite

Martensite is a supersaturated solid solution of carbon in iron produced by rapid cooling. In the untempered condition it is very hard and brittle. Martensite is normally “tempered”-heat treated to reduce its carbon content by the precipitation of carbides-to provide a controlled combination of high strength wear resistance and ductility [8].

2.1.4.5. Austenite

Normally a high temperature phase consisting of carbon dissolved in iron, it can exist at room temperature in austenitic and austempered cast iron. In austenitic irons, austenite is stabilized by nickel in the range of 18-36% [28]. In austempered irons, austenite is produced by a combination of rapid cooling which suppress the formation of pearlite and the supersaturation of carbon during austempering, which depress the start of the austenite-to-martensite transformation far below room temperature. In austenitic irons, the austenite matrix provides ductility and toughness at all temperatures, corrosion resistance and good high temperature properties, especially under thermal cycling conditions. In austempered ductile iron stabilized austenite, in

volume 15 fractions up to 40% in lower strength grades, improves toughness and ductility and response to surface treatments such as fillet rolling [8].

2.1.4.6. Bainite

Bainite is a mixture of ferrite and carbide, which is produced by alloying or heat treatment [8].

2.1.5. Types of ductile iron

With a high percentage of graphite nodules present in the structure, mechanical properties are determined by the ductile iron matrix. The importance of matrix in controlling mechanical properties is emphasized by the use of matrix names to designate the following types of Ductile Iron [7, 8].

2.1.5.1. Ferritic Ductile Iron

Graphite spheroids in a matrix of ferrite provide an iron with good ductility and impact resistance and with a tensile and yield strength equivalent to low carbon steel. Ferrite ductile iron can be produced as-cast but may be given an annealing heat treatment to assure maximum ductility and low temperature toughness [7, 8].

2.1.5.2. Ferrito- Pearlitic Ductile Iron

These are the most common grade of ductile iron and are normally produced in the as-cast condition. The graphite spheroids are in a matrix containing both ferrite and pearlite. Properties are intermediate between ferritic and pearlitic grades, with good machinability and low production costs [7, 8].

2.1.5.3. Pearlitic Ductile Iron

Graphite spheroids in a matrix of pearlite result in an iron with high strength, good wear resistance, and moderate ductility and impact resistant. Machinability is also superior to steels of comparable physical properties. The preceding three types of Ductile Iron are the most common and are usually used in the as-cast condition, but ductile iron can also be alloyed/or heat treated to provide the following grades for a wide variety of additional applications [7, 8].

2.1.5.4. Martensitic Ductile iron

Using sufficient alloy additions to prevent pearlite formation, and a quench-and-temper heat treatment produces this type of ductile iron. The resultant tempered martensite matrix develops very high strength and wear resistance but with lower levels of ductility [7, 8].

2.1.5.5. Austenitic Ductile Iron

Alloyed to produce an austenitic matrix, this ductile iron offers good corrosion and oxidation resistance, and good strength and dimensional stability at elevated temperatures [7, 8].

2.1.5.6. Austempered Ductile iron (ADI)

ADI, the most recent addition to the ductile iron family, is a sub-group of ductile iron produced by giving conventional ductile iron a special austempering heat treatment. Nearly twice as strong as pearlitic ductile iron, ADI still retains high elongation and toughness. This combination provides a material with superior wear resistance and fatigue strength [7, 8].

2.1.6. Different grades of ductile iron

Table2.1. Different grades of ductile iron [9].

Grade and heat treatment	Tensile strength (MPa)	Yield strength minimum (MPa)	Percentage of elongation	Brinell hardness	Matrix microstructure
60-40-18 (1)	414	276	18	149-187	Ferrite
65-45-12 (2)	448	310	12	170-207	Ferrite + Pearlite
80-55-06 (3)	552	379	6	197-255	Pearlite + ferrite
100-70-03 (4)	690	483	3	217-269	Perlite
120-90-02 (5)	828	621	2	240-300	Tempered martensite

2.1.7. Factors that affect the properties of the ductile iron

Ductile iron is a special kind of material which exhibits a good combination of strength with ductility ensuring its huge application in heavy engineering industries. This is due to very typical

microstructure owing to its chemical composition, heat treatment practice and processing variables. Some lists of important constituents which are responsible for its typical mechanical properties are discussed below.

2.1.7.1. Effect of graphite shape

As would be expected from the dramatic differences in mechanical properties between Gray and Ductile Irons, that modularity plays a significant role in determining properties within the Ductile Iron family. The relationship between modularity and Dynamic Elastic Modulus not only emphasizes the strong influence of modularity on DEM, but also indicates that DEM values obtained by sonic testing can be used to measure modularity (graphite volume and nodule count should be relatively constant).

Nodularity, and the morphology of the non-spherical particles produced as modularity decreases, exerts a strong influence on the yield and tensile strengths of Ductile Iron. The relationships between strength and nodularity for ferritic irons in which modularity has been changed by two methods: through magnesium control, or through lead control. When nodularity is decreased by reducing the amount of residual magnesium (the most common spheroidizing agent used in commercial Ductile Iron) the nodules become elongated, but do not become sharp or "spiky". The result is a 10% decrease in yield strength and a 15% decrease in tensile strength when modularity is reduced to 30%. Small additions of lead reduce modularity by producing inter granular networks of "spiky" or plate-like graphite which result in dramatic reductions in tensile properties.

The effect of nodularity on pearlitic Ductile Irons can be determined by comparing the tensile properties, at constant carbide levels, of irons with nodularities of 90, 70 and 40%. Compared to the Mg-controlled loss of nodularity for the ferritic iron, the pearlitic iron is much more sensitive to reduced nodularity. Second, at low carbide levels typical of good quality Ductile Iron, there is relatively little loss of strength as the nodularity decreases to 70% but as nodularity deteriorates further, strength decreases more rapidly.

The effect of nodularity on elongation can be inferred by considering the influence of nodularity on the difference between the yield and tensile strengths, which is proportional to elongation. Both Mg- and Pb-controlled losses in nodularity reduce the difference between the yield and tensile stresses, indicating that loss of nodularity results in reduced elongation. The dramatic decrease in tensile strength produced by lead control indicates that the formation of spiky, intercellular graphite can severely embrittle Ductile Iron.

Designers can virtually eliminate the effect of nodularity on tensile properties by specifying that the nodularity should exceed 80-85% and that there should be no intercellular flake graphite. These criteria can be met easily by good production practices which ensure good nodularity through Mg control and prevent flake or spiky graphite by a combination of controlling flake-producing elements and eliminating their effects through the use of small additions of cerium [8].

2.1.7.2. Effect of Nodule Count

Nodule Count, expressed as the number of graphite nodules/MM^2, also influences the mechanical properties of Ductile Iron, although not as strongly and directly as graphite shape. Generally, high nodule count indicates good metallurgical quality, but there is an optimum range of nodule count for each section size of casting, and nodule counts in excess of this range may result in a degradation of properties. Nodule count per se does not strongly affect tensile properties, but it has the following effects on microstructure, which can significantly influence properties,

- Nodule count influences the pearlite content of as-cast Ductile Iron. Increasing the nodule count decreases the pearlite content, decreasing strength and increasing elongation.
- Nodule count affects carbide content. Increasing the nodule count improves tensile strength, ductility and machinability by reducing the volume fractions of chill carbides, segregation carbides, and carbides associated with "inverse chill".
- Matrix homogeneity is influenced by nodule count. Increasing the nodule count produces a finer and more homogeneous microstructure. This refinement of the matrix structure reduces the segregation of harmful elements which might produce intercellular carbides, pearlite or degenerate graphite.

- Nodule count affects graphite size and shape. Increasing nodule count results in a decrease in nodule size which improves tensile, fatigue and fracture properties. Inoculation practices used to improve nodule count often make the nodules more spherical. Thus, high nodule count is generally associated with improved nodularity [8].

2.1.7.3. Effect of Matrix

In Ductile Irons with consistent modularity and nodule count and low porosity and carbide content, mechanical properties are determined primarily by the matrix constituents and their hardness. For the most common grades of Ductile Iron, the matrix consists of ferrite and/or pearlite. Ferrite is the purest iron phase in Ductile Iron. It has low strength and hardness, but high ductility and toughness and good machinability. Pearlite is an intimate mixture of lamellar cementite in a matrix of ferrite. Compared to ferrite, pearlite provides a combination of higher strength and hardness and lower ductility. The mechanical properties of ferritic/pearlitic Ductile Irons are, therefore, determined by the ratio of ferrite to pearlite in the matrix. This ratio is controlled in the as-cast condition by controlling the composition of the iron, taking into account the cooling rate of the casting. It can also be controlled by an annealing heat treatment to produce a fully ferritic casting, or by normalizing to maximize the pearlite content [8].

2.1.7.4. Effect of silicon

Silicon enhances the performance of Ductile Iron at elevated temperatures by stabilizing the ferritic matrix and forming a silicon-rich surface layer which inhibits oxidation. Stabilization of the ferrite phase reduces high temperature growth in two ways. First, silicon raises the critical temperature at which ferrite transforms to austenite. The critical temperature is considered to be the upper limit of the useful temperature range for ferritic Ductile Irons. Above this temperature the expansion and contraction associated with the transformation of ferrite to austenite can cause distortion of the casting and cracking of the surface oxide layer, reducing oxidation resistance. Second, the strong ferritizing tendency of silicon stabilizes the matrix against the formation of carbides and pearlite, thus reducing the growth associated with the decomposition of these phases at high temperature. The oxidation protection offered by silicon increasing with

increasing silicon content. Silicon levels above 4% are sufficient to prevent any significant weight gain after the formation of an initial oxide layer [10].

2.1.7.5. Effect of molybdenum

Molybdenum, whose beneficial effect on the creep and stress-rupture properties of steels is well known, also has a similar influence on Ductile Irons. The addition of 0.5 % molybdenum to ferritic Ductile Iron produces significant increases in creep and stress rupture strengths, resulting in high temperature properties that are comparable to those of a cast steel containing 0.2 % carbon and 0.6 % manganese [10].

2.1.7.6. Effect of Manganese

The decomposition of austenite to ferrite plus graphite or to pearlite in spheroidal graphite (SG) cast iron is known to depend on a number of factors among which are the nodule count, the cooling rate, and the alloying additions (Si, Mn, Cu, etc.).The detrimental effect of Mn on the growth kinetics of ferrite during the decomposition of austenite in the stable system is explained in terms of the driving force for diffusion of carbon through the ferrite ring around the graphite nodules. Finally, it is found that copper can have a pearlite promoter role only when combined with a low addition of manganese. As it is a mild pearlite promoter, with some required properties like proof stress and hardness to a small extent, Mn retards the onset of the eutectoid transformation, decreases the rate of diffusion of C in ferrite and stabilizes cementite (Fe3C), but the problem here is the embrittlement caused by it, so the limiting range would be 0.18-0.5%. [8, 9, 10]

2.1.7.7. Effect of Copper

The effect of various additions of copper and the cooling rate on the temperature of the onset of the stable and metastable eutectoid reactions describes the conditions for the growth of ferrite and of pearlite. These reactions can develop only when the temperature of the alloy is below the lower boundary of the ferrite/austenite/graphite or ferrite/austenite/cementite related three-phase field. Copper is a strong pearlite promoter. It increases the proof stress with also the tensile strength and hardness with no embrittlement in matrix. So in the pearlitic grade of the ductile iron the copper is kept between 0.4-0.8percent and is a contaminant in the ferritic grade [8, 9,10].

2.1.7.8. Effect of Nickel

It helps in increasing the U.T.S without affecting the impact values .So it can be used in the range of 0.4-2.0%. It strengthens ferrite, but has much less effect than Silicon in reducing ductility. As a Mild pearlite promoter, increases proof stress but little effect on tensile strength, but there is the danger of embrittlement with the large additions, in excess of 2%. Due to the high cost it is generally present as traces in the matrix. The irons treated with nickel have nodular graphite in a matrix of austenite with rather more carbide than the untreated irons [8, 9, 10].

2.2. Austempered ductile iron

2.2.1. Austempering

The austempering process was first developed in the early 1930's as a result of work that Bain, et al, was conducting on the isothermal transformation of steel. In the early 1940's Flinn applied this heat treatment to cast iron, namely gray iron. In the 1950's, both the material, ductile iron, and the austempering process had been developed [11].

Process

1) Heat castings in a molten salt bath to austenitizing temperature (815-927^{O}c)

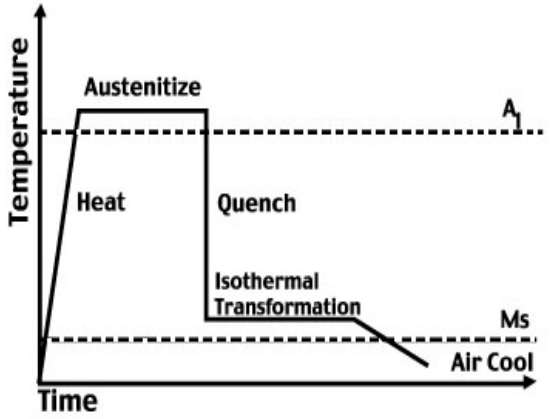


Fig.2.2. Austempering process [11]

2) Hold at austenitizing temperature to dissolve carbon in austenite.

3) Quench quickly to avoid pearlite.

4) Hold at austempering temperature (232-400^{0}C) in molten salt bath for isothermal transformation to ausferrite [12].

Consistent control of times and temperatures throughout the entire process

1) Initial austenitizing times and temperatures (1550° to 1700° F.) are controlled to ensure formation of fine grain austenite and uniform carbon content in the matrix. The precise temperature is grade dependant.

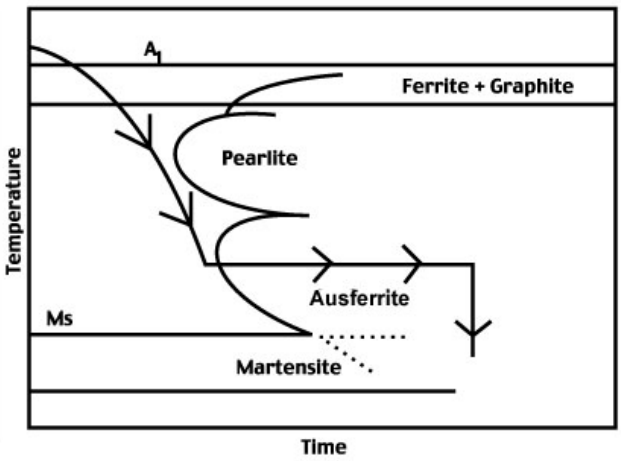


Fig.2.3. Control of time and temperature on the process [12].

2) Quench time must be controlled within a few seconds, to avoid formation of pearlite around the carbon nodules, which would reduce mechanical properties. Quench temperatures (450° to 750° F.) must stay above the point of martensite formation.

3) In the austempering step which follows austenitizing, the temperature of the final salt bath must also be closely controlled. The austempering step is also precisely time-controlled, to avoid over- or under-processing. By the end of this step, the desired ADI ausferrite structure has developed [12].

2.2.1.1. Austenitizing

The austenitizing temperature controls the carbon content of the austenite which, in turn, affects the structure and properties of the austempered casting. High austenitizing temperatures increase the carbon content of the austenite, increasing its hardenability, but making transformation during austempering more problematic and potentially reducing mechanical properties after austempering. (The higher carbon austenite requires a longer time to transform to ausferrite). Reduced austempering temperatures generally produce ADI with the best properties but this requires close control of the silicon content, which has a significant effect on the upper critical temperature of the Ductile Iron. Austenitizing time should be the minimum required to heat the entire part to the desired austenitizing temperature and to saturate the austenite with the equilibrium level of carbon, (typically about 1.1-1.3%). In addition to the casting section size and type, the austenitizing time is affected by the chemical composition, the austenitizing temperature and the nodule count [13].

2.2.1.2. Austempering

Austempering is fully effective only when the cooling rate of the quenching apparatus is sufficient for the section size and hardenability of the component. The minimum rate of cooling is that required avoid the formation of pearlite in the part during quenching to the austempering temperature. The critical characteristics are as follows:

- Transfer time from the austenitizing environment to the austempering environment
- The quench severity of the austempering bath
- The maximum section size and type of casting being quenched
- The hardenability of the castings
- The mass of the load relative to the quench bath.

The use of a correctly designed austempering system with a suitably high quench severity, and the correct loading of castings, can minimize hardenability requirements of the casting resulting in significant savings in alloy costs [13].

2.2.2. Austempered ductile iron

Austempered ductile iron is the most recent addition of the ductile iron family. It is produsedby giving conventional ductile iron to austmepering heat treatment [13]. Unlike conventional "as-cast" irons, its properties are achieved by heat treatment, not by specific addition. Therefore the only prerequisite for a good ADI is a quality ductile iron [15].

Austempered Ductile Iron (ADI) offers the best combination of low cost, design flexibility, good machinability, high strength-to-weight ratio and good toughness, wear resistance and fatigue strength properties. Because it can be cast like any other member of the Ductile Iron family it offers all the production advantages of a conventional Ductile Iron casting. Subsequently it is subjected to the austempering process to produce mechanical properties that are superior to conventional ductile iron, cast and forged aluminum and many cast and forged steels [17].

The mechanical properties of properties of the ductile iron and austempered ductile iron are primarily determined by the metal matrix. The matrix in conventional ductile iron is controlled by mixture of pearlite and ferrite. The properties of austempered ductile iron is due to its unique matrix of acicular ferrite and carbon stabilized austenite, is called ausferrite. The austempering process has been utilized since the 1930 on cast and wrought steels but this process first commercially applied to ductile iron in 1972 [14].

2.2.2.1. Microstructure

Ductile Cast Iron undergoes a remarkable transformation when subjected to the austempering heat process. A new microstructure (ADI) results with capability superior to many traditional, high performance, ferrous and aluminum alloys.

To optimize ADI properties for a particular application the austempering parameters must be carefully selected and controlled. Castings are first austenitised to dissolve carbon, then quenched rapidly to the austempering temperature to avoid the formation of deleterious pearlite or martensite.

While the casting is held at the austempering temperature nucleation and growth of acicular ferrite occurs, accompanied by rejection of carbon into the austenite. The resulting microstructure, known as "Ausferrite", gives ADI its special attributes. Ausferrite exhibits twice the strength for a given level of ductility compared to the pearlitic, ferritic or martensitic structures formed by conventional heat treatments.

Because the carbon rich austenite phase is stable in Austempered Ductile Iron it enhances the bulk properties. Furthermore, while the austenite is thermodynamically stable, it can undergo a strain-induced transformation when locally stressed, producing islands of hard martensite that enhance wear properties. This behavior contrasts with that of the metastable austenite retained in steels, which can transform to brittle martensite [18].

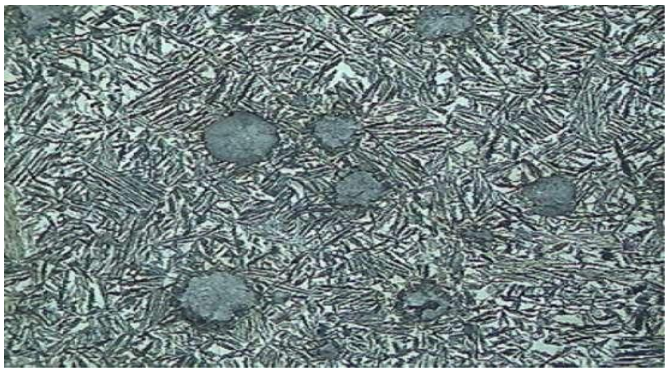


Fig 2.4.Microstructure of austempered ductile iron [18].

2.2.2.2. Composition

In many cases, the composition of an ADI casting differs little from that of a conventional Ductile Iron casting. When selecting the composition, and hence the raw materials, for both conventional Ductile Iron and ADI, consideration should be given first to limiting elements which adversely affect casting quality through the production of nonspheroidal graphite, or the formation of carbides and inclusions, or the promotion of shrinkage. The second consideration is the control of carbon, silicon and the major alloying elements that control the hardenability of the iron and the properties of the transformed microstructure. When determining the alloying

requirements both the section size and type and the severity (or speed) of the austempering quench must be considered [13].

For a typical salt quench with agitation section sizes up to about 3/8 inch (10 mm) can be successfully through hardened without pearlite with even unalloyed Ductile Iron. For a highly agitated austemper quench with water saturation section sizes of up to ¾ inch (20 mm) can be through hardened with no additional alloying. For castings of heavier section size selective alloying is required to through harden the parts and avoid pearlite in the heat treated microstructure [13].

2.2.2.3. Different grades of austempered ductile iron

Table2.2. Grades of austempered ductile iron [16].

Ref. Grade #	ASTM A897 Grade	Tensile Strength	Yield Strengths	Elongation	Brinell Hardness
1	130-90-09	130,000 p.s.i.	90,000 p.s.i.	9 %	269-341
2	150-110-07	150,000 p.s.i	110,000 p.s.i	7 %	302-375
3	175-125-04	175,000 p.s.i.	125,000 p.s.i.	4 %	341-444
4	200-155-02	200,000 p.s.i	155,000 p.s.i.	2 %	388-477
5	230-185-1	230,000 p.s.i.	185,000 p.s.i.	1 %	402-512

2.2.2.4. Effect of alloying elements

2.2.2.4.1. Carbon

Increasing carbon in the range 3 to 4% increases the tensile strength but has negligible effect on elongation and hardness. Carbon should be controlled within the range 3.6-3.8% except when deviations are required to provide a defect-free casting [13-14].

2.2.2.4.2. Manganese

Manganese can be both a beneficial and a harmful element. It strongly increases hardenability, but during solidification it segregates to cell boundaries where it forms carbides and retards the austempering reaction. As a result, for castings with either low nodule counts or section sizes greater than 3.4 in. (19mm), manganese segregation at cell boundaries can be sufficiently high to produce shrinkage, carbides and unstable austenite. These microstructural defects and inhomogeneities decrease machinability and reduce mechanical properties. To improve properties and reduce the sensitivity of the ADI to section size and nodule count, it is advisable to restrict the manganese level in ADI to less than 0.3%. The use of high purity pig iron in the ADI charge offers the twin advantages of diluting the manganese in the steel scrap to desirable levels and controlling undesirable trace elements [13-14].

2.2.2.4.3. Silicon

Silicon is one of the most important elements in ADI because it promotes graphite formation, decreases the solubility of carbon in austenite, increases the eutectoid temperature, and inhibits the formation of bainitic carbide. Increasing the silicon content increases the impact strength of ADI and lowers the ductile-brittle transition temperature. Silicon should be controlled closely within the range 2.4-2.8% [13-14].

2.2.2.4.4. Nickel

Up to 2% nickel may be used to increase the hardenability of ADI. For austempering temperatures below 675^{o}F (350^{o}C) nickel reduces tensile strength slightly but increases ductility and fracture toughness [13-14].

2.2.2.4.5. Molybdenum

Molybdenum is the most potent hardenability agent in ADI, and may be required in heavy section castings to prevent the formation of pearlite. However, both tensile strength and ductility decrease as the molybdenum content is increased beyond that required for hardenability. This

deterioration in properties is probably caused by the segregation of molybdenum to cell boundaries and the formation of carbides. The level of molybdenum should be restricted to not more than 0.2% in heavy section castings [13-14].

2.2.2.5. Advantages of Austempered Ductile Iron:

ADI provides high strength, good fatigue properties, superior wear qualities, excellent toughness, and cost-effectiveness.

2.2.2.5.1. Tensile and Yield Strength:

ADI's tensile and yield strengths are at least twice those of standard ductile irons.

2.2.2.5.2. Fatigue Strength:

ADI's fatigue strength is typically 50% higher than that of standard ductile irons. It can be further increased by shot peening or fillet rolling. The lower hardness grades of ADI work well in structural applications.

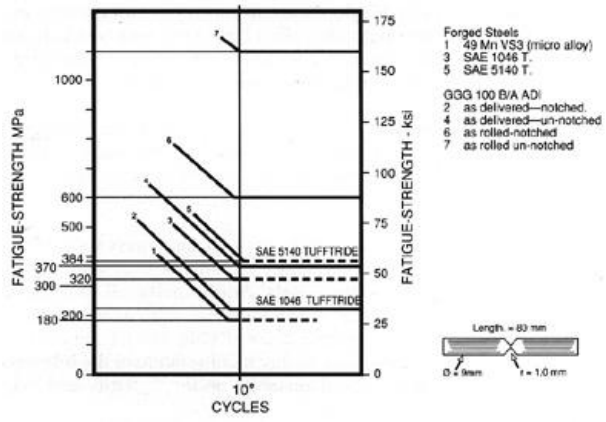


Fig 2.5.Fatigue strength compared to other materials [14].

2.2.2.5.3. Toughness:

ADI's excellent impact and fracture-toughness properties make it ideal for applications such as ground-engaging tools.

2.2.2.5.4. Less weight

ADI weighs only 2.4 times more than aluminum and is 2.3 times stiffer. ADI is also 10% less dense than steel. Therefore, when you compare the relative weight per unit of yield strength of ADI with that of various aluminums and steels, it is easy to see the engineering and design advantages inherent in ADI.

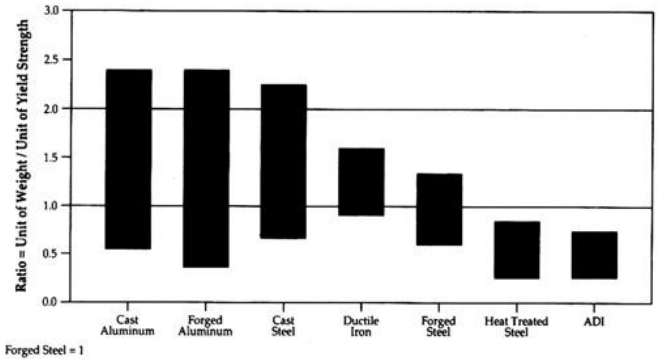


Fig2.6.Less weight compared to the other steels [14].

2.2.2.5.5. Wear Characteristics:

The higher hardness grades of ADI are excellent for wear applications. Unlike case-hardened materials, typically the ADI is uniformly hardened throughout the part. Also, ADI work-hardens when stressed. This produces a thin surface of very hard martensite where wear resistance is most needed.

2.2.2.5.6. Cost-effectiveness:

ADI is usually 15% to 20% less costly than steel forgings or castings. It is the most economical way of obtaining tensile, yield, or fatigue strength. ADI often competes favorably with heat-treated and alloy steels for heavy-duty applications where reliabilty is crucial. It is a useful upgrade from standard grades of ductile iron. In some cases it replaces manganese steel and nickel-chrome iron. Because of ADI's high strength-to-weight ratio, it has even replaced aluminum where the design allows reduced section sizes [14].

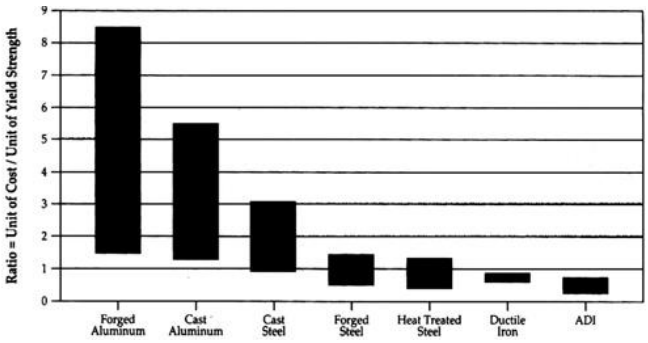


Fig2.7.Relative cost per unit of yield strength [14].

2.2.2.6. Properties of ADI Compared to Steel:

- ADI is much easier to cast than steel
- ADI is approximately 9% lighter than steel
- ADI has minimal draft requirements compare with steel forgings
- ADI loses less of its toughness than steel at sub-zero temperatures
- ADI work hardens when stressed
- ADI has more damping capacity than steel [19].

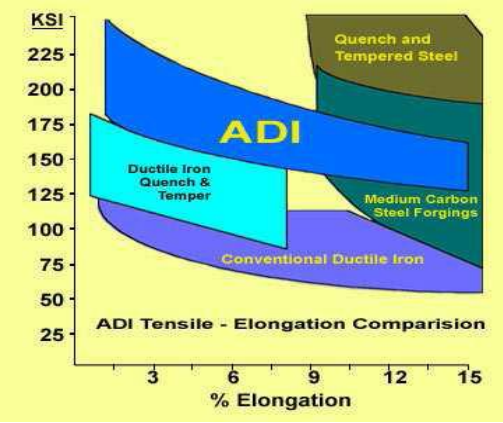


Fig2.8.Properties of ductile iron compared steels [19].

2.2.2.7. Disadvantages of ductile iron

Materials specifiers should look beyond limited mechanical property data when replacing steel parts with ADI. For example, welding is not recommended for ADI parts. In some instances, the stiffness of the design must be increased to compensate for ductile iron's lower modulus of elasticity. Also, larger fillet radii are required than for steel to avoid stress concentrations. To take maximum advantage of ADI when substituting for forgings, some designs should be modified. Another desirable property of ADI is its work-hardening, which provides better rolling and sliding wear properties. However, because of this characteristic, consideration must be given to the sequence of operations when machining is required. The lower hardness grades can be machined after heat-treatment, but the higher hardness grades must be machined before heat treatment [21].

2.2.2.8. Applications of austempered ductile iron

The development and commercialization of Austempered Ductile Iron (ADI) has provided the design engineer with a new group of cast ferrous materials which offer the exceptional combination of mechanical properties equivalent to cast and forged steels and production costs similar to those of conventional Ductile Iron. In addition to this attractive performance: cost ratio, ADI also provides the designer with a wide range of properties, all produced by varying the heat treatment of the same castings, ranging from 10-15% elongation with 125 ksi (870 MPa) tensile strength, to 250 ksi (1750 MPa) tensile strength with 1-3% elongation. Although initially hindered by lack of information on properties and successful applications, ADI has become an established alternative in many applications that were previously the exclusive domain of steel castings, forgings, weldments, powdered metals and aluminum forgings and castings [22].

The ADI market represents nearly all segments of manufacturing. Bellow fig shows the approximate break down of the ADI market.

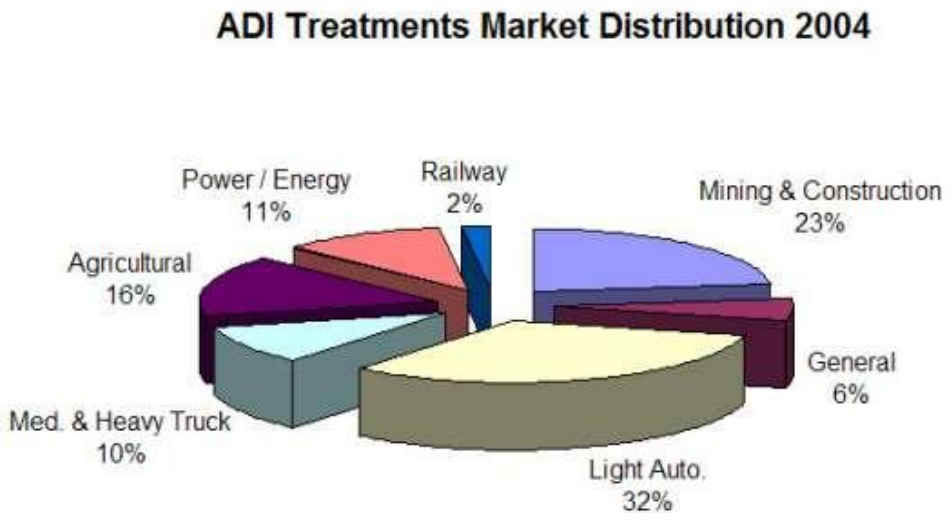


Fig 2.9. ADI market distribution [18].

Heavy Truck and Bus Components

Economic growth drives the need to haul heavier loads over longer distances, resulting in more time between vehicle maintenance and some difficult engineering challenges. The Heavy Truck industry recognised the potential benefits of Austempering solutions many years ago. Manufacturers took advantage of the versatility of ADI to introduce innovative light weight, high performance parts. Diesel Engine Timing Gears, Hypoid Ring and Pinion Gears, Jack Stand Gears, Wheel Hubs, Suspension Brackets these are some components which are manufactured by using austempering ductile iron [18-22].

Railway

The Railway industry is constantly looking to improve its products and the safety and efficiency of rail transport. The railroad industry uses ADI for suspension housings, top caps and friction wedges, track plates, repair vehicle wheels, nipper hooks, and car wheels [18-22].

Construction Equipment

Heavy duty and hard working, construction equipment can benefit greatly from the use of tough, wear resistant Austempered Irons and Steels. Whether for ground engaging components such as

bucket teeth or engine and powertrain parts, ADI and other Austempered materials can improve the performance of your equipment [18-22].

Light Vehicle

The automotive industry is constantly looking to increase performance, and reduce the cost and weight of the vehicles they produce. Austempered materials have a proven track record of providing strength and dependability for safety components, suspension systems, and drivetrain applications [18-22].

Miscellaneous Industrial

Miscellaneous industrial applications include brackets, lever arms, knuckles, shafts, cams, sway bars, sleeves, clevises, conveyor components, jack components, bushings, rollers, molding line components, fixtures, gears, sprockets, deck plates, and all sorts of power transmission and structural components [18-22].

Agricultural

Farming and agricultural applications for ADI include plow points, till points, trash cutters, seed boots, ammonia knives, gears, sprockets, knotter gears, ripper points, tractor wheel hubs, rasp bars, disk parts, bell cranks, lifting arms, and a great variety of parts for planters, plows, sprayers and harvesters [22].

Sporting Goods

Even the sports goods industry has adopted ADI for its high strength to weight and superior wear resistance. Bobsleigh runners, Sword blades, Gun components are manufacturing by using austempered ductile iron [18].

Defense

The defense industry has been relatively slow to adopt ADI, however some of the applications include track links, armor, ordnance and various hardware for trucks and armored vehicles [22].

Gears/Shafts/Powertrain

For high performance gear and power train manufacturers, Austempered materials offer greater wear resistance, reduced noise, improved bending and contact fatigue, as well as increased strength and durability. Diesel Engine Timing Gears, Hypoid Ring and Pinion Gears, Off-Highway Drive Axles, Ring Gears, Gear Housings, Sprockets, CV Joints, Differential Housings, Wheel Hubs etc are prepared by using austempered ductile iron [18].

Chapter 3

A brief discussion of previous works

CHAPTER 3 A brief discussion on previous work

Form the available literatures, it is quite evident that many attempts were made to understand and predict the behaviors of austempered ductile iron that includes the study of ausferrite matrix structure and the response of matrix structure to heat treatment, structure and properties correlation, and its mechanical properties with different variables and possible applications. A brief review of some literatures in these areas is presented here under.

Olivera Eric, Dragan Rajnovic, Slavica, Leposava Sidjanin, T.Jovanovic have studied on the macrostructure and fracture of two types of austempered ductile iron, one is alloyed with copper and another one is alloyed with copper and nickel and observed the effect of copper and copper plus nickel on the microstructure and impact properties of the two types austempred ductile irons. They told that addition of copper plus nickel delays the transformation kinetics of the residual austenite resulting in a shift of the maximum of volume fraction of retained austenite to 3 hours of austempering, compared to 2 hours in austempered ductile iron alloyed with copper. In the same time, they observed higher maximum value of the volume fraction of retained austenite in austempered ductile iron alloyed with copper plus nickel. In the same austempered ductile iron a substantial plastic deformation at the peak of impact energy is associated with the highest volume fraction of retained austenite. So they have been demonstrated that the volume fraction of retained austenite strongly effects impact energy of both irons, i.e. with content retained austenite up to maximum value impact energy increases, then a decrease occurs with the decrease of retained austenite [23].

J. Zimba, D.J. Simbi, E. Navara have studied the abrasive wear and mechanical properties of the austempered ductile iron and compared these properties with the quenched and tempered steel. In this work they have taken one type of ductile iron sample and two types of steel samples and austmpered the ductile iron sample at different temperatures and times, and steel samples were quenched & tempered at different temperatures. They observed that as the austempering temperature is increases so does the ferrite lath spacing and the volume fraction of retained austenite. In mechanical properties, the tensile strength and hardness decrease with austempering temperature while the elongation and impact toughness indicate significant

increase as the austempering temperature is raised. The good wear resistance exhibited by austempered ductile iron despite the low initial hardness can be attributed to the surface transformation of retained austenite to martensite during abrasion, i.e. during abrasion; there is a surface transformation of retained austenite to martensite. Due to this the surface hardness and wear resistance of austempered ductile iron increase [24].

Z.K.Fan and R.E.Smallman have studied the fracture behavior of the austempered aluminum spheriodal graphite iron. For that they have taken the specimens of Aluminum spheriodal graphite iron containing by weight 3.2%C, 2.2%A1, 0.3%Si were austenitised at 950°C for 2 hours and then austempered at 300°C or 400°C for times up to 6 hours, polished and were squeezed to fracture. From the observations they demonstrated that Cracks always originate from graphite nodules in austempered ductile iron. The easiest propagation path of a crack in austempered ductile iron is along the austenite ferrite interfaces and the propagation path of a crack depends on the orientation relationship of bainitic ferrite laths with the applied load direction, and also on whether there is carbide precipitation in the bainitic ferrite laths or at the ferrite austenite interfaces. Carbides precipitated in bainitic ferrite laths promote the passage of cracks through the ferrite laths, but do not significantly influence the fracture mode and Carbides precipitated at the ferrite austenite interfaces clearly promote crack propagation along the interfaces and change the fracture mode from ductile to cleavage in austempered ductile iron. In the absence of carbide precipitation in the matrix, the fracture mode of austempered ductile iron is typically ductile. Cracks often propagate along the interfaces which lie approximately normal to the applied load direction, but cut through the bainitic ferrite laths which lie parallel to the applied load direction [25].

Uma Batra, S.Ray and S.R.Prabhakar studied on the variation in the austempered microstructure, the volume fraction of retained austenite, the average carbon content of retained austenite, their product and the size of bainitic ferrite needles with austempering temperature for 0.6% Cu alloyed ductile iron. In this work they have taken copper alloyed ductile iron specimens and austempered at different temperatures and times. From their work they observed that increasing austempering temperature changes the bainite Morphology from lower bainitic to upper bainite. The average austenite volume fraction of austenite, its carbon content, and the size of bainitic ferrite also increase with increasing austempering temperature. Increasing the austempering time initially Increases the amount of retained austenite and its carbon content, both of which then

reach a plateau. The plateau extends over a period of stability of retained austenite, after which there is a decrease of both [26].

F.Y. Hung, L.H. Chen, T.S. Lui studied the particle erosion of upper bainitic austempered ductile iron. In this work they have taken aductile iron sample and austempered at 420^0C and at different times. Then these upper bainitic austempered ductile iron (ADI) specimens were eroded by Al2O3 particles of 275μm grit size under the average particle velocity of 73ms−1. They observed that the austempered specimen of lower austempering time which contains largest amount of retained austenite and no austempered carbide is more erosion resistance than other ADI specimens and the same cast iron of other common matrix structures. If austempering time is increased then brittle cracks will induce at normal impact and shift the impact angle of maximum erosion rate to a higher one. They also demonstrated that € carbide will form upon the particle impingement and retained austenite is not only phase to transformed during the erosion process but also may be possible for the bainitic ferrite because its carbon concentration is higher than equilibrium[27].

Uma Batra, Subrata Ray, and S.R. Prabhakar studied the effect of alloying elements on the austempering process, austempered microstructure, and structural parameters of two austempered ductile irons (ADI) containing 0.6% Cu and 0.6% Cu +1.0% Ni as the main alloying elements. They used optical metallography and x-ray diffraction to study the changes in the austempered structure. They studied effect of alloying additions on the austempering kinetics using the Avrami equation. They observed significantly more upper bainite in the austempered Cu-Ni alloyed ADI than in Cu alloyed ADI. The volume fraction of retained austenite, the carbon level in the retained austenite, and the product of retained austenite and carbon content in an austempered structure of Cu-alloyed ADI are higher than in Cu-Ni-alloyed ADI. The austempering Kinetics is slowed down by the addition of Ni [28].

O. Eric, M. Jovanovic, L. Šidjanin and D. Rajnovic studied on the microstructure and mechanical properties of the austempered ductile iron which is alloyed with copper, Nickel and molybdenum. In this work they austenised the samples at 860^0C for one hour and then austempered at 320^OC and 400^0C in the form 0.5 to 5 hours. They observed from their work is that the Austempering at 320oC in the range between 2 and 5h produces a typical austempered ductile iron microstructure consisting of free bainitic ferrite and a stable, highly carbon enriched retained austenite. The maximum value of impact energy (133 J) corresponds to the maximum

volume fraction of retained austenite (40 vol%) which was reached after 2,5h. The whole range of austempering time at 400oC is distinguished by the presence of blocky austenite in which martensite was formed during subsequent cooling to the room temperature. During austempering at 400^{o}C yield strength, tensile strength and ductility are twice as lower than at 320^{o}C. The low values of tensile properties coincide with the appearance of martensite in the microstructure [29].

J. Aranzabal, I. Gutierrez, J.M. Rodriguez-Ibabe, and J.J. UrcolaR have studied on the the influence of the amount and morphology of austenite phase on the mechanical properties (proof stress, ultimate tensile strength (UTS),elongation and toughness) at different austempering conditions. They concluded from their work that the short time treatments lead to deteriorated mechanical properties in accordance with the presence of untempered martensite. The combination of long times and high temperatures of austempering produces a similar trend associated, in this case, with the decomposition of the austenite, into ferrite plus coarse carbides, that takes place during the heat treatment. At the lowest temperature, the austenite is plastically stable due to the higher carbon content and to the finer distribution of this phase in the microstructure. The bainitic ferrite and the austenite contribute in this case to the proof stress of the material, and the increase of the austenite volume fraction has beneficial effect on the toughness. The increase of the austenite volume fraction as the treatment temperature increases has two different effects on the material properties: a decrease of the carbon content and a coarser morphology of this phase. After 300^{0} C isothermal treatments at intermediate times, the austenite is plastically stable at room temperature and contributes, together with the bainitic ferrite, to the proof stress and the toughness of the material. For austenite volume fractions higher than 25 pct, the proof stress is controlled by this phase and the toughness depends mainly on the stability of austenite. In these conditions (370^{0}C and 410^{0}C treatments), the present material exhibits a transformation-induced plasticity effect, which leads to an improvement in ductility. It is shown that the strain level necessary to initiate the martensitic transformation induced by deformation depends on the carbon content of the austenite. The martensite formed under TRIP conditions can be of two different types: ‘‘autotempered’’ plate martensite, which forms at room temperature from an austenite with a quasi-coherent epsilon carbide precipitation, and lath martensite nucleated at twin boundaries and twin intersections [30].

A.S.M.A. Haseeb, Md. Aminul Islam, Md. Mohar Ali Bepari studied the behavior of ductile iron heat treated by two different procedures, quenching &tempering and austempering to identical matrix hardness. For that they have taken samples of ductile iron, hest treated (austempered and quenching & tempering) and carried out wear tests using a pin-on-disc type apparatus under dry sliding conditions. They have observed that under all test conditions austempered ductile iron exhibits a better wear resistance than quenched & tempered ductile iron, although both have an identical chemical composition and matrix hardness. The relative superiority of austempered ductile iron becomes even more pronounced at higher load and longer sliding distance. Micro hardness measurement below wear scar reveals that the hardness of austempered ductile iron increases while that of quenched and tempered iron decreases during the wear process [31].

Srinivasamurthy daber, K.S.Ravishankar, P.Prasad Rao have studied the influence of austenitising temperature on the formation of strain-induced martensite in austempered ductile iron. For that they have taken Ductile iron containing 1.5 wt.% nickel, 0.3 wt.% molybdenum and 0.5 wt.% copper was subjected to austempering treatments which consisted of three austenitising temperatures, namely 850, 900 and 950^{o} C, and three austempering temperatures, namely 300, 350 and 400^{0} C. They were carried out tensile tests under all the heat-treatment conditions and strain-hardening behaviour was studied by applying Hollomon equation. Microstructures were studied by optical microscopy and X-ray diffraction. They observed that the retained austenite can transform to martensite through a TRIP like phenomenon. The propensity to transform to martensite under strain depends to a large extent on the austenitising temperature. As the austenitising temperature is increased the tendency to transform to martensite increases at all the austempering temperatures. High austenitising temperature together with high austempering temperature forms retained austenite with low stability, and therefore greater tendency to form martensite under strain [32].

M.Nili Ahmadabadi, H,M.Ghasemi and M.Osia have studied the effect of austempering process on the wear behavior of austempered ductile iron ADI. For that they have taken a 0.75 wt. % Mn ductile iron with different nodule counts was austempered by conventional and successive austempering processes at 315 and 375^{0} C for different periods. They are concluded from their sliding wear tests on specimens with optimum mechanical properties austempered by different

processes is that the delamination mechanism as a dominant wear mechanism. from the mechanical and wear test resultsthey told that successive austempering process improves both mechanical properties and wear resistance of ADI in comparison with conventional austempering process. The specimens with lower nodule count longer solidification time have lower wear rate than specimens with higher nodule count shorter solidification time. High carbon content retained austenite along with good mechanical properties is supposedly the main reason for improvement of wear resistance of HLAT specimens [33].

Uma Batra, S.Ray and S.R.Prabhakar studied The effect of austempering temperature and time on tensile properties such as 0.2% proof stress, ultimate tensile strength (UTS), percentage of elongation, and quality index and these properties have correlated with the structural parameters of the austempered ductile iron microstructure. For that they have a ductile iron containing 0.6% copper as the main alloying element was austenitized at 850 °C for 120 min and was subsequently austempered for 60 min at austempering temperatures of 270, 330, and 380 °C. The samples were also austempered at 330 °C for austempering times of 30-150 min. They concluded from there is that, In Cu-alloyed ADI, when the austempering temperature increases from 270-380 °C, the proof stress and UTS decrease due to the change in morphology of the bainitic ferrite. However, the percentage of elongation and the QI increase monotonically. The proof stress, UTS, and the percentage of elongation, as well as the QI, are relatively low at short tAs, and these values increase as the austempering process progresses.The proof stress may decrease at longer tAs, while the UTS remains, more or less, constant. Austempering the Cu-alloyed ductile iron for 60 min at 270, 330, or 380 °C resulted in an ADI close to the 1200/4, 1050/7, and 850/10 grades of ASTMA 897. The UTS and the percentage of elongation of this ADI alloy that was austempered at 330 °C fall below those specified in the ASTM standard for tAs less than 30 min; however, these properties improve for tAs of 60-150 min [34].

A.Kutsov, Y.Taran, K.Uzlov, A.Krimmel and M.Evsyukov studied the kinetics of kinetics of bainite transformation under isothermal conditions in Ni-Mn-Cu-Mo alloyed ductile iron.they studied the foemation of upper and lower bainite in the ductile iron described by different C-shaped curves.They concluded fom their work is that morphology of the bainite changes accordingly: the upper bainite has a feathery-like morphology and the lower bainite has a plate-

like one. These facts are, probably, a result of different crystallographic shears during the formation of the upper and lower bainites. Acomparison of the dilatometrical data with the X-ray results shows that the bainite transformation ceases once the carbon concentration in low carbon austenite reaches a certain value. It is suggested that this concentration corresponds to curve and the composition of high carbon austenite is increasing. It seems to be that the increase of the bainitic a-phase volume fraction results in an increase of the volume fraction of high carbon austenite [35].

U. Batra was studied the fracture behavior of copper-alloyed austempered ductile iron using metallography and fractography. She investigated the the effect of austempering temperature on the microstructure, mechanical properties, fracture behavior under tensile and impact loading, and fracture mechanism. She concluded from their work is that When the austempering temperature is increased from 270 to 380°C, the volume fraction of retained austenite, the carbon content of the austenite, and the size of the bainitic ferrite needle increase. The morphology of the bainitic ferrite changes from lower to upper. The hardness, 0.2% proof stress, and UTS of the ADI decrease, but the impact energy increases with the increase in austempering temperature from 270 to 380°C. The percent elongation increases with the increase in austempering temperature from 270 to 330°C but decreases on further increase in temperature to 380°C. In ADI austempered at 270°C, the deformation is limited to near the nodule only. However, it spreads into the matrix for ADIs austempered at the higher austempering temperatures of 330 and 380°C. The crack generally initiates from the graphite nodule surface and propagates through the matrix of bainitic ferrite and retained austenite. It normally propagates through bainitic ferrite/austenite interfaces when ferrite makes an angle greater than 45° with the applied load, but it cuts through bainitic ferrite when the cluster of bainitic ferrite makes an angle less than 45° with the applied load. Intercellular segregation and nonmetallic inclusions are the other probable locations for crack growth [36].

C.Hakan Gür, Volkan Kilicli, Mehmet Erdogan have studied the mechanical properties of austempered ductile iron achieved through the heat treatment is conducted in a restricted time and temperature frame called the “processing window”. In this study they hav investigated MBN response and variations in microstructure and mechanical properties of austmpered ductile iron.

MBN measurements are sensitive to the fine evolutions of the austempering stages of austempered ductile iron. Martensite volume fraction gradually decreases and finally disappears with increasing the austempering time while the transformed austenite content decreases and acicular ferrite contents increases. By measuring the MBN parameters such as, the height and the position of MBN peak, the changes in the microstructure and corresponding variations in yield and tensile strengths, and total elongation can be estimated non-destructively [37].

C.Valdes, M.J. Perez Lopez, M. Figueroa, and L.E. Ramirez have studied Microstructural features and mechanical properties of austempered ductile iron with duplex matrix unalloyed and alloyed with 1Ni-0.24 Mo by optical microscopy, tensile and impact test. For that they heated the ductile iron specimens to the austenitizing temperature in the range of 780 to 830^0C for 90 minutes and then austempered at 375^0C for 60 minutes. From their work, they observed that Ascast microstructure was constituted by a ferritepearlite mixture of the bull-eye type with an average of graphite nodularity of 93%.UTS, elongation and impact strengh strongly depend on amounts of pro-eutectoid ferrite and ausferrite present after heat treatment.Unalloyed and 1Ni-0.24Mo ductile iron treated in the intercritical region between 800 – 830^0C, exhibited the highest impact strength from 140 to 145 J and from 100 to 130 J,respectively, due to presence of duplex matrix structure [38].

C.Z. Wu, Y.J. Chen andT.S. Shih have studied the phase transformation of austmepered ductile iron by microjet impact. For that they have austempered the ductile iron specimens at 320^0C and 360^0C with ultrasonic vibration treatment. They found from their work is that the content and morphology of retained austenite have a fundamental influence on the mechanical properties of ADI. Good ductility is exhibited in the matrix microstructure where a large volume fraction of austenite has been retained and most island-like austenite is uniformly distributed over the matrix, as in the case developed from Ni- and Cu-alloyed ADI. After subjecting to ultrasonic treatment, some island-like austenite is found to undergo a phase transformation of austenite to martensite induced by shear stresses from impact of microjets and shock waves, while some stringer-type austenite is found to precipitate carbides. After the process, microhardness values are enhanced along with an increased cumulative treatment time. The values obtained in intercellular regions are much higher due to Mn segregation. The stress-induced transformed

martensite analyzed by EPMA is found to have a higher content of Mn for island-like austenite, which appears without microcracks, and that having a lower content of Mn usually shows microcracks after ultrasonic treatment. The elastic strain-energy density estimated from a microjet impact on the surface of ADI varied from 5.1×10^3 to 9.2×10^4 J/m^3. In the homogeneous nucleation of a martensite nucleus, the elastic strain energy density is about 8.6×10^7J/m3. Apparently, this estimated elastic strain-energy density is far ower than the energy necessary for homogeneous nucleation of martensite [40].

Yoon-Jun Kim, Hocheol Shin, Hyounsoo Park and Jong Dae Lim hve studied how the mechanical properties of the austempered ductile cast iron varying with the autempering temperature. For that they have austenitized the samples alloyed with copper and molybdenum at 910^{o}C for one hour and autmepered at 350 and 410^{0}C temperatures. From their work they concluded that Cu and Mo alloyed iron blocks were cast and heat treated. In order to see the effect of austempering temperature on mechanical properties, blocks were austenitized at 910 °C for 90 min, then quenched and held at 350, 370, 390 and 410 °C for 90 min. It was found that the higher austempering temperature, the higher ductility. The highest ductility was obtained from410 °C austempered samples. However,tensile strength was highest for 350 °C austempered cast iron. Based upon mechanical property investigations, ADIs produced at higher isothermal tempering temperatures such as 390 °C and 410 °C can be categorized as an ASTM grade1. While those austempered at lower temperatures such as 350 °C and 370 °C can be grouped as ASTM grade 2. Copper and molybdenum addition plays effective role in the formation of ausferrite structure as well as increment of mechanical properties such as tensile strength and hardenability [41].

Dong Cherng WEN and Tien Shou LEI have studied the mechanical properties and microstructure of low alloyed ductile iron in the upper ausferrite region. For that they have taken the samples of ductile iron alloyed with 0.77% copper and 0.5% nickel and austenitized at 900^{o}C and austempered at 400^{o}C.they found from their work is that The martenslte content of ADI had a significant influence on Its mechanica] propertles. As martensite content Increased, ductility and toughness decreased obviously. The effect of martensite on reducing mechanical properties coud be eliminated after tempering at 200^0 C. Ductility and toughness could be increased without

decreasing the previous strength, and these strengthening effects were particularly evident at 3-50 % martensite content. Tempering at 200^0 C could shorten the austempering time in getting the samelevel as the peak values of mechanical properties of ADI treated with single austempering, and could extend the effective range of austempering time. From the observation of mechanical properties and microstructure changes, it was evident that the use of processing window defined by resisitivity curve in selecting the isothermal holding time in austempering was effective and direct. When ductile iron was austempered within this processing window the mechanical properties satisfied the standard requirementwere obtained.

Chapter4
Experiment

CHAPTER 4 Experiment

Two grades of ductile iron samples have used in the experiment which are produced commercial foundry known as L&T Kansbhal. The difference between these two grades were one contains copper and another without copper. Chemical composition of the two grades of ductile iron samples given below in the table.

Table4.1.composition of the samples

	C	Si	Mn	Cr	Ni	Mg	Cu	S	P
With copper	3.55	2.1	0.18	0.03	0.22	0.038	0.49	0.009	0.024
Without copper	3.57	2.22	0.23	0.03	0.32	0.045	0.001	0.011	0.026

4.1.Test Specimen Preparation:

For different tests the solid block of ductile iron was cut to thickness of 4-6 mm using power hacksaw. Then they are grinded, polished and machined to the dimension required for various experiments to be carried out.

4.2. Heat Treatment (Austempering):

No of samples of each grade have taken and heated to 900^0C for one hour (austenisation) and then transferred quickly to a salt bath (salt combination was 50 wt % NaNO3 and 50 wt % KNO3) maintained at different temperatures(250^0C,300^0C,350^0C) for half an hour, one hour, one and half an hour and two hours.

4.3. Hardness Measurement:

The heat treated samples of dimension 8×8×3 mm were polished in emery papers(or SiC papers) of different grades for hardness measurement. Rockwell Hardness test was performed at room

temperature to measure the macro hardness of the ductile iron specimens in A scale. The load was applied through the square shaped diamond indenter for few seconds during testing of all the treated and untreated samples. Four measurements for each sample were taken covering the whole surface of the specimen and averaged to get final hardness results. A load of 60 kg was applied to the specimen for 30 seconds. Then the depth of indentation was automatically recorded on a dial gauge in terms of arbitrary hardness numbers. Then these values were converted to in terms of required hardness numbers (as Brielle's or Vickers hardness numbers).

4.4. Tensile Testing:

Tensile test were carried out according to ASTM (A 370-2002). A specimen of "Dog Bone Shape" shown in figure 3.2 was prepared for tensile test, which were machined to 6mm gauge diameter and 30 mm gauge length. Test was conducted by using universal testing machine (UTM 100) as per ASTM standard.

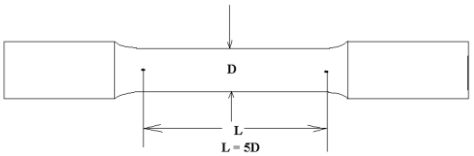


Fig.4.1. Specimen used for tensile properties

Advanced materials are used in a wide variety of enviournments and at different temperature and pressure. It is necessary to know the elastic and plastic behavior of these materials under such conditions. Such properties as tensile strength, creep strength, fatigue strength, fracture strength, fracture toughness, and hardness characterize that behavior. These properties can be measured by mechanical tests.

4.5. Scaning Electron Microscopy.

4.5.1. Micro-structural observations:

The samples were prepared for micro structural analysis. From each specimen a slice of 4 mm is cut to determine the microstructure. These slices are firstly mounted by using Bakelite powder then polished in SiC paper of different grades (or emery papers) then in 1 μm cloth coated with diamond paste. The samples were etched using 2% natal (2% conc. Nitric acid in methanol

solution). Then the microstructures were taken for different heat treated specimen by using Scanning Electron Microscopy (SEM).

4.5.2. Fractoraography:

Fracture surface or surface morphology of the samples which fractures in different manners (ductile, Brittle and mixed mode fracture) after tensile test for treated and untreated condition are analyzed by using Scanning Electron microscopy (SEM).For this samples were cleaned with Acetone to remove any dust or impurity on the surface of specimens before SEM.

4.6. X-Ray Diffraction studies:

The XRay diffraction (XRD) analysis was performed for few selected samples. This technique was used to estimate the volume fractions of retained austenite and ferrite in the material after treatment. XRD was performed 30 KV and 20 mA using a Cu- Kα target diffractmeter. Scanning was done in angular range 2θ from 40° to 48° and 70° to 92° at a scanning speed of 1°/min. The profile were analyzed on computer by using X' Pert High Score Software to obtain the peak position and integrated intensities of the autenite and ferrite. By comparing these intensities the volume fractions of retained austenite and ferrite were estimated.

Chapter 5
Results & discussion

CHAPTER 5 Results & discussion

In the present research work effect of different variables like austempering time, austempering temperature and alloying of copper on properties and microstructure of ductile iron have been studied.

5.1. The mechanical properties

Table5.1.mechanicle properties of ADI without copper

	Time(min)	UTS (MPa)	YS (MPa)	%Elongation	Hardness(RA)
250	30	997	795	1.9	75
	60	1139	957	2.4	80
	90	1124	927	2.8	79
	120	1116	906	2.8	78
300	30	831	639	3.7	69
	60	983	806	4.2	73
	90	965	759	4.8	71
	120	976	788	4.7	72
350	30	724	539	5.9	65
	60	871	691	6.7	69
	90	849	673	7.2	68
	120	861	687	7.1	67

Table 5.2.mechanicle properties of ADI with copper

Temperature(°C)	Time (min)	UTS(MPa)	YS(MPa)	%Elongation	Hardness(RA)
250	30	1039	834	1.5	76
	60	1181	995	2.1	82
	90	1162	967	2.4	80
	120	1168	978	2.3	79
300	30	873	685	3.1	71
	60	1017	825	3.5	74
	90	1034	858	3.7	72
	120	1030	851	3.8	73
350	30	778	591	5.2	68
	60	928	735	5.8	72
	90	921	733	5.9	70
	120	907	716	6	69

5.1.1. Effect of autempering time on UTS

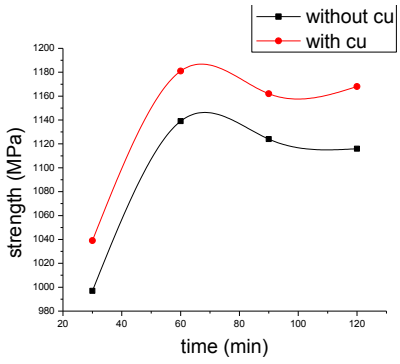


Fig 5.1

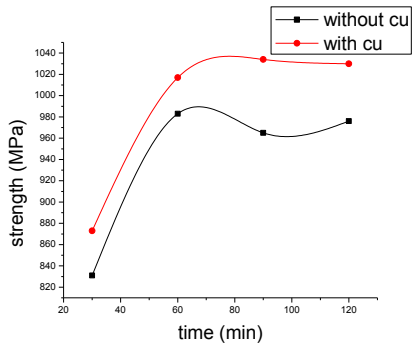


fig 5.2

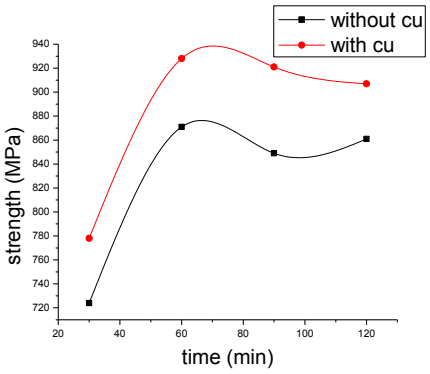


Fig 5.3

Fig 5.1, 5.2,&5.3 are showing the variation of tensile strength with respect to the austempering time at temperature 250^{o}C, 300^{o}C &350^{0}C respectively for two grades (one with copper and another without copper). Tensile strength is increasing from half an hour austempering time to one hour, from one hour to one and half an hour it is decreasing and from one and half an hour to two hours sometimes increasing and sometimes increasing. Overall it is observed that tensile strength is increasing from half an hour to one hour and for one hour, one and half an hour and two hours tensile strength almost same i.e. not showing significance difference for both the grades. Austempered ductile iron alloyed with cooper is showing little bit higher strengths than the unalloyed austempered ductile iron.

5.1.2. Effect of autempering time on elongation

Fig5.4, 5.5, &5.6 are showing the variation of elongation with respect to the austempering time at temperature 250^{o}C, 300^{o}C &350^{0}C respectively for two grades (one with copper and another without copper). Elongation is increasing from half an hour austempering time to one hour, from.

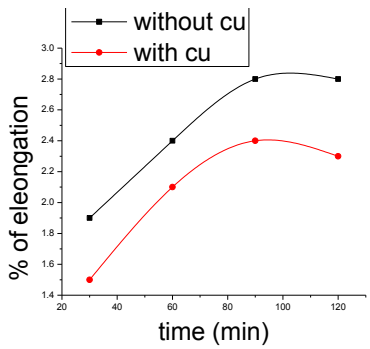


Fig 5.4

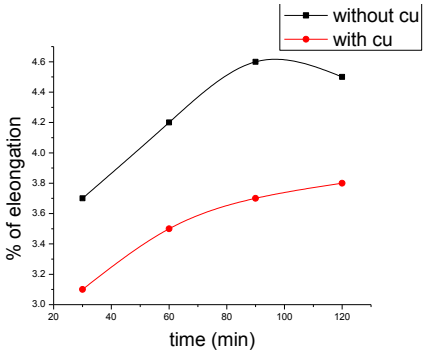


fig 5.5

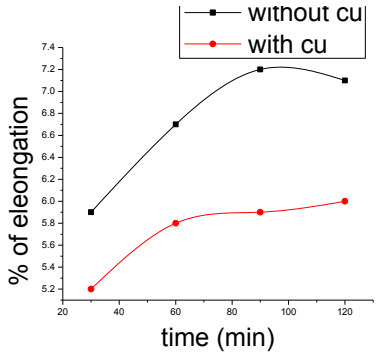


Fig 5.6

one hour to one and half an hour it is decreasing and from one and half an hour to two hours sometimes increasing and sometimes increasing. Overall it is observed that Elongation is increasing from half an hour to one hour and for one hour, one and half an hour and two hours tensile strength almost same i.e. not showing significance difference for both the grades. Austempered ductile iron alloyed with cooper is showing little bit lower elongation than the unalloyed austempered ductile iron.

5.1.3. Effect of austempering time on hardness

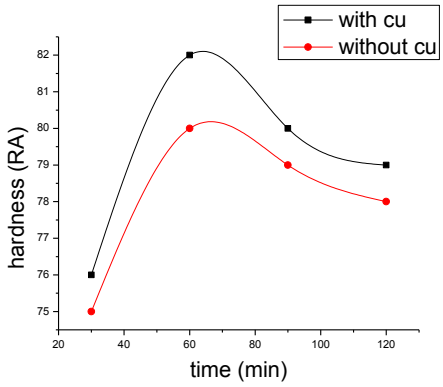


Fig 5.7

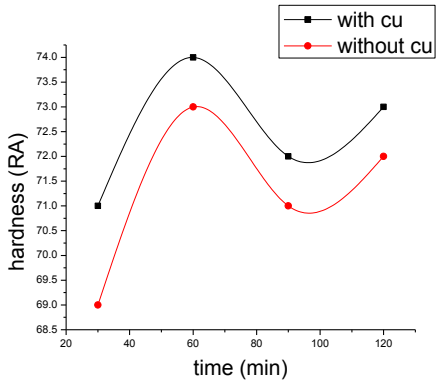


fig 5.8

Fig5.7,5.8&5.9 are showing the variation of hardness with respect to the austempering time at temperature 250^{o}C, 300^{o}C &350^{0}C respectively for two grades (one with copper and another without copper). Hardness is increasing from half an hour austempering time to one hour, from one hour to one and half an hour it is decreasing and from one and half an hour to two hours

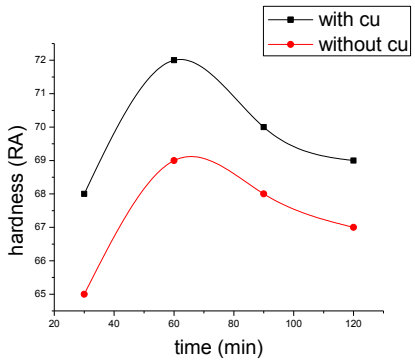


Fig 5.9

sometimes increasing and sometimes increasing. Overall it is observed that hardness is increasing from half an hour to one hour and for one hour, one and half an hour and two hours tensile strength almost same i.e not showing significance difference for both the grades. Austempered ductile iron alloyed with cooper is showing little bit higher hardness than the unalloyed austempered ductile iron.

5.1.4. Effect of austempering temperature on UTS

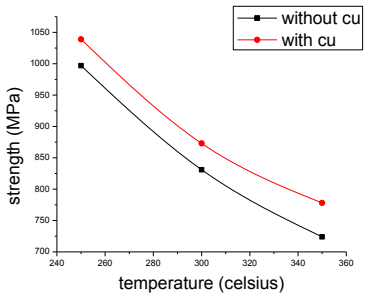


Fig 5.10

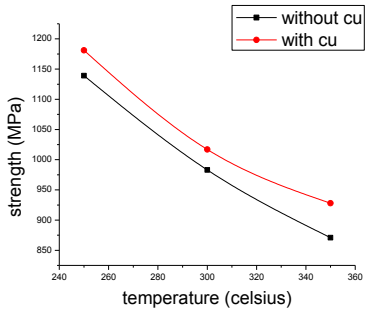


fig 5.11

Fig 5.10, 5.11, 5.12&5.13 are showing the variation of tensile strength with respect to the austempering temperature for ½ hour, 1 hour, 1 ½ and two hours respectively for both the grades (one with copper and another without copper). Tensile strength is decreasing with respect to the austempering temperature. i.e with increasing austmpering temperature tensile strength is decresing in both grades.

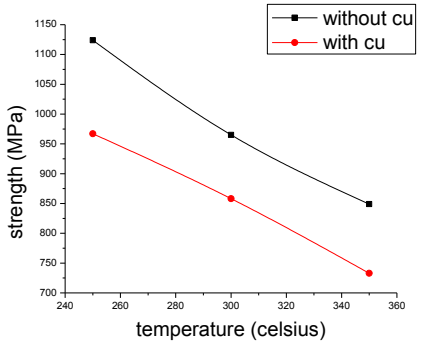


Fig5.12

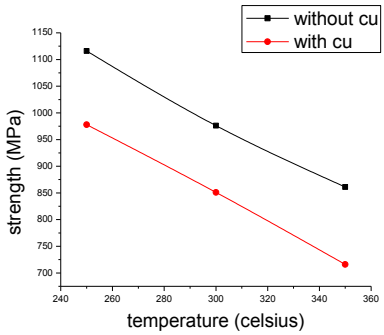


fig 5.13

5.1.5. Effect of austempering temperature on elongation

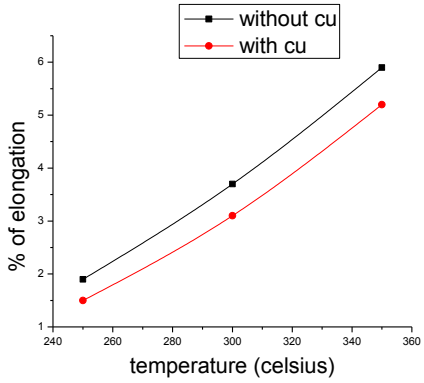


Fig 5.14

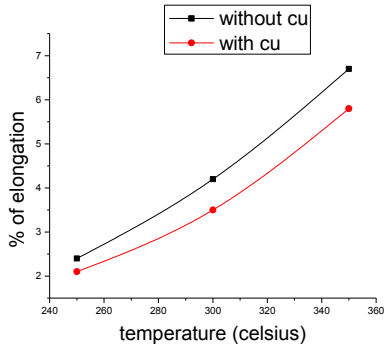


fig 5.15

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Fig 23, 24, 25 &26 are showing the variation of elongation with respect to the austempering temperature for ½ hour, 1 hour, 1 ½ hours and two hours respetedly for both the grades (one with copper and another without copper) . Elongation is incresing with respect to the austempering temperature. i.e with increasing autmpering temperature elongation is incresing in both grades.

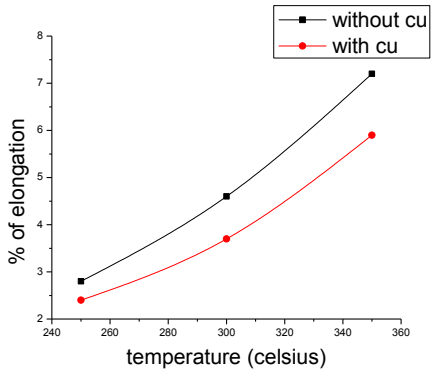

Fig 5.16

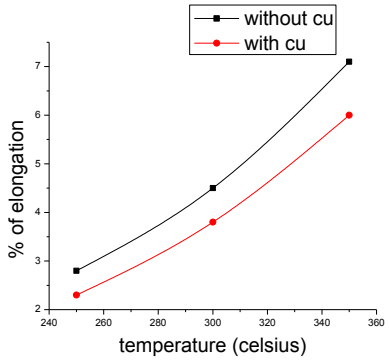

fig 5.17

5.1.6. Effect of austempering temperature on hardness

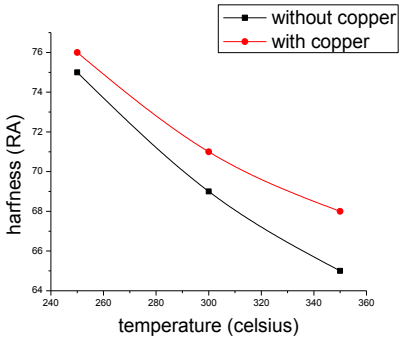

Fig 5.18

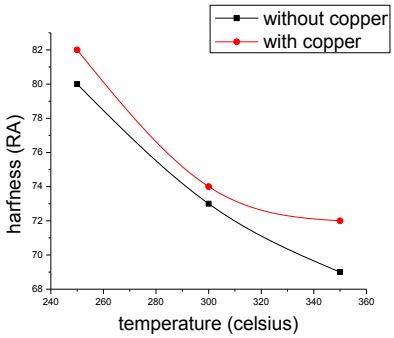

fig 5.19

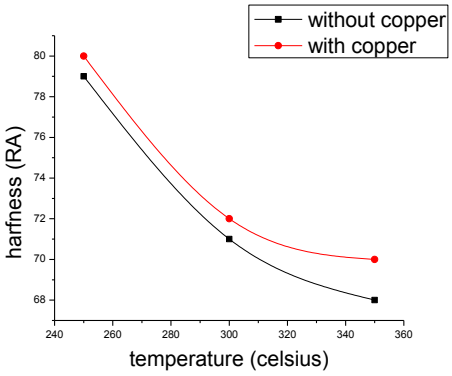

Fig 5.20

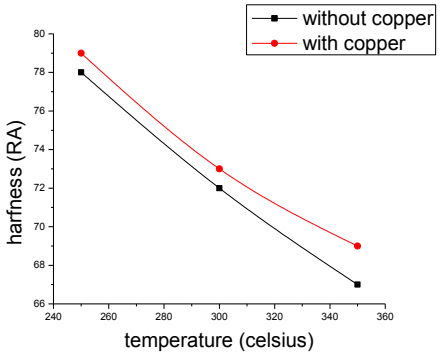

fig 5.21

Fig 28,29,30&31 are showing the variation of hardness with respect to the austempering temperature for ½ hour, 1 hour, 1 ½ hours and two hours respectively for both the grades(one with copper and another without copper) . Hardness is decreasing with respect to the

austempering temperature. i.e with increasing austmpering temperature hardness is decresing in both grades.

5.2. X-ray diffraction analysis

5.2.1. Austempered ductile iron without copper

The XRD pattern of austempered ductile iron (without copper) austempered at different temperatures and different times as shown bellow figers.

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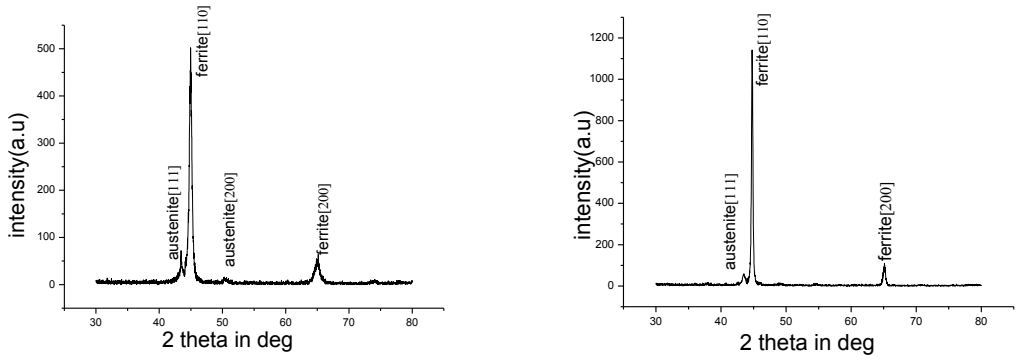

Fig.5.22. Shows the XRD pattern of ductile iron sample austempered at 250^{o}C for (a) 1 hr and (b) for 1 ½ hr.

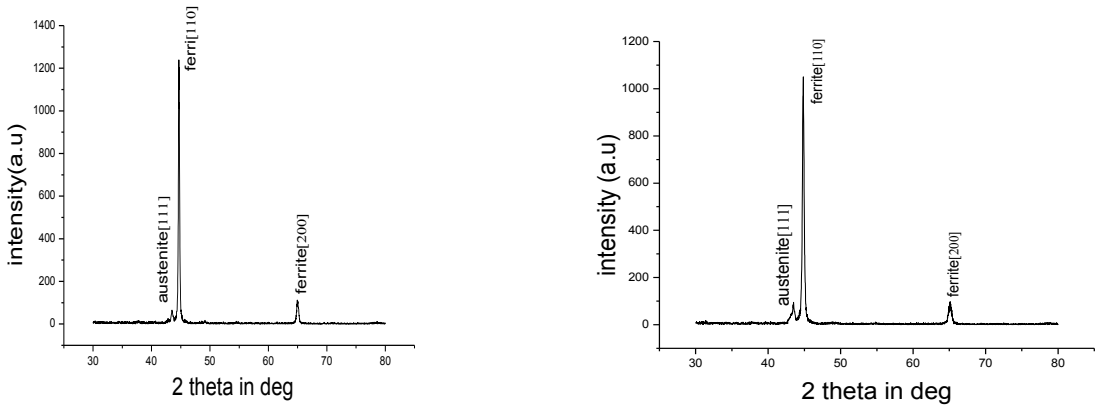

Fig.5.23. shows the XRD pattern of ductile iron austempered (a) at 250^{0}C for 2 hours and (b) at 300^{0}C for 1hr.

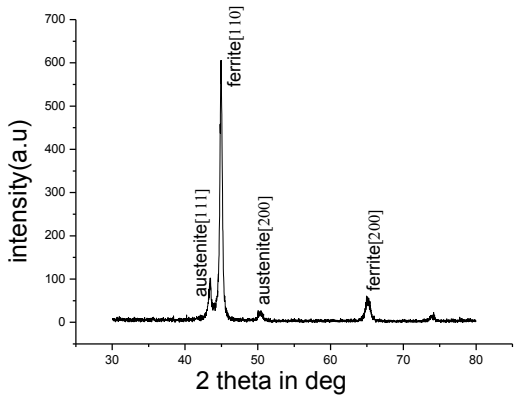

Fig.5.24. shows the XRD pattern of ductile iron austempered at 350^0C for 1 hour.

In the XRD pattern it is observed that the austenite (111) lines and ferrite (110) are identified nearly in all cases. The maximum intensity of the austenite (111) line is increasing with increasing temperature but ferrite (110) line is increasing with increasing austempering time and decreasing with increasing temperature.

5.2.2. Austempered ductile iron with copper

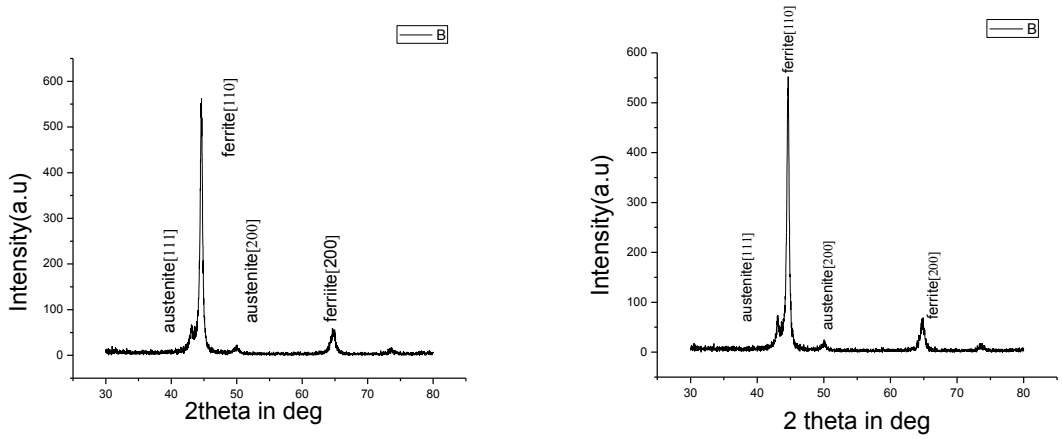

Fig.5.25. shows the XRD pattern of alloyed ductile iron austempered at 250^oC for 1hour and 2 hours.

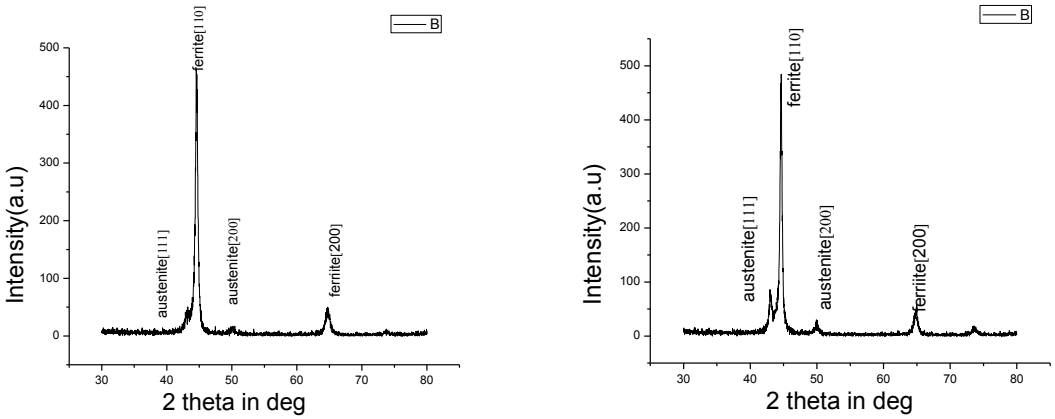

Fig.5.26. shows the XRD pattern of alloyed ductile iron austempered at 250^{o}C for ½ hour and 350^{o}C for 1 hour.

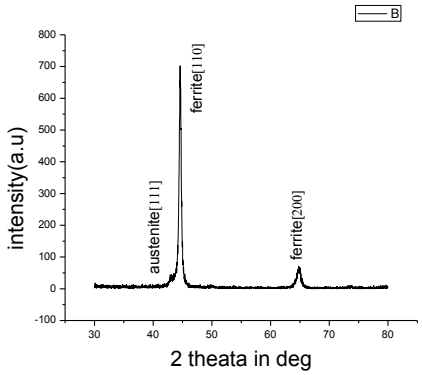

Fig.5.27. shows the XRD pattern of alloyed ductile iron austempered at 300^{o}C for 1 hour.

In the XRD pattern it is observed that the austenite (111) lines and ferrite (110) are identified nearly in all cases. The maximum intensity of the austenite (111) line is increasing with increasing temperature but ferrite (110) line is increasing with increasing austempering time and decreasing with increasing temperature.

5.3. Scanning electron microscopy

5.3.1. Microstructure

The microstructures of unalloyed and alloyed ductile iron samples were observed under the scanning electron microscope and are shown in following fig.

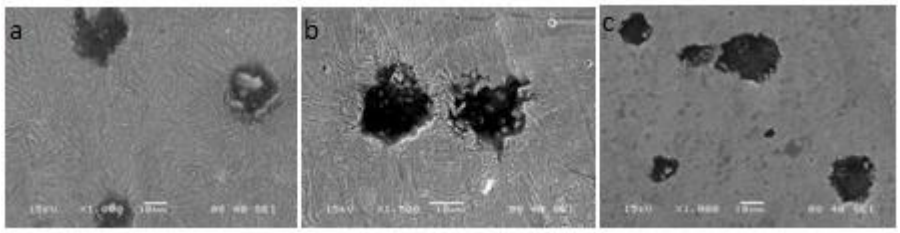

Fig.5.28.microstructure of the autsmpered ductile iron (without copper) austempered at (a) 250^{o}C for ½ hour (b) 350^{0}C for 1 hour (c) 300^{o}C for 1 ½ hour.

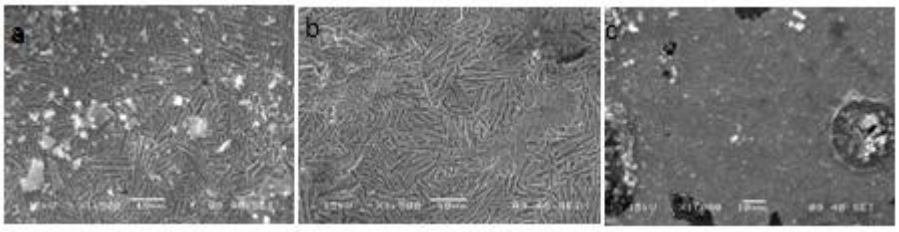

Fig.5.29. microstructure of the autsmpered ductile iron (with copper) austempered at (a) 350^{o}C for 1 hour (b) 250^{0}C for ½ hour (c) 250^{o}C for 2 hours.

In the above microstructure it is observed that the samples which are autempered at higher temperatures having upper bainitic structure and the samples which are austempered at lower temperatures are having lower bainitic structure. When the austempering temperature increasing the morphology of bainite also changing from acicular to plate like. The amount of retained austenite is increasing at higher temperature. At lower austempering temperatures the strength is higher. There is no significance difference between copper alloyed ductile iron and ductile iron without copper.

5.3.2. Fracrography

The morphology of fracture surfaces are analyzed by scanning electron microscopy and pictures are given bellow.

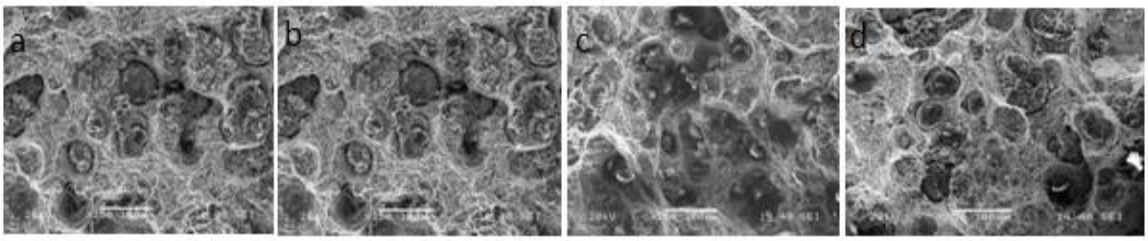

Fig5.30. Fracture surfaces of the copper alloyed ductile iron which is austempered at 250^0C for (a) 2hrs (b) 1 ½ hrs(c) ½ hr (d) 1hr.

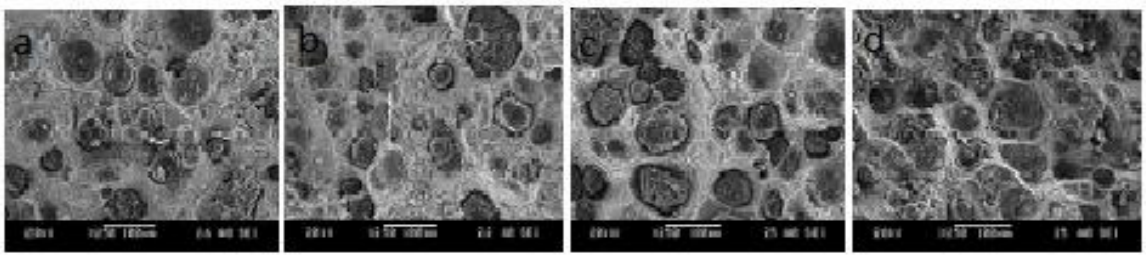

Fig.5.31. fracture surfaces of the austemered ductile (without copper) which austmpered at 250^0C for (a) ½ hours (b) 1 hours, (c) 1 ½ hour and (d) 2 hours.

In the above pictures it is observed that, at lower treatment times, the fracture pattern (in both the grades) shows a mixed mode of fracture (ductile and brittle), because of the presence of retained austenite and some amount of martensite. But as austempering time is increased, the fracture bears a dimple type appearance because of the disappearance of martensite phase. It is observed that the dimple size increases but the number of dimples decreases with increasing austempering temperature. Dimple size increased with increasing austempering temperature, which indicates improvement in ductility.

Chapter 7
Conclusions

CHAPTER 7 Conclusions

1) As the austempering temperature is increasing hardness and tensile strength are decreasing and elongation is increasing in both the copper alloyed ductile iron and un alloyed ductile iron.
2) As the austempering time is increasing tensile strength, hardness and elongation are increasing in both the grades.
3) The ductile iron alloyed with copper is showing little bit high tensile strength and hardness but lower elongation compared with unalloyed ductile iron.
4) In microstructure austenite is increasing with increasing austempering temperature and ferrite is increasing with increasing austempering time in both the grades.
5) The samples which are autempered at higher temperatures having upper bainitic structure and the samples which are austempered at lower temperatures are having lower bainitic structure in both the grades.
6) The fracture surfaces showed a mixed mode of fracture for shorter austempering time. The percentage of dimple fracture (ductile) then increased with time and with increasing temperature also size of dimple is increasing which indicates improvement in ductility.

Future scope of the work

Austempered ductile iron has found enormous applications in recent years due to its high strength and hardness, with ductility and toughness. It has started to replace steel in some structural applications. Engineering applications of ductile iron in as cast and different heat treated conditions are growing day by day. More work is needed to improve the properties of ductile iron through find out the effect of different alloying elements and heat treatment process on the ductile iron.

Chapter 8
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CHAPTER 8 References

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